

Developing Sustainable Spacecraft Water Management Systems

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Abstract

It is well recognized that water handling systems used in a spacecraft are prone to failure caused by biofouling and mineral scaling, which can clog mechanical systems and degrade the performance of capillary-based technologies. Long duration spaceflight applications, such as extended stays at a Lunar Outpost or during a Mars transit mission, will increasingly benefit from hardware that is generally more robust and operationally sustainable over time.

This paper presents potential design and testing considerations for improving the reliability of water handling technologies for exploration spacecraft. Our application of interest is to devise a spacecraft wastewater management system wherein fouling can be accommodated by design attributes of the management hardware, rather than implementing some means of preventing its occurrence.

Introduction

Development of spacecraft life support hardware over the past few decades has focused primarily on microgravity applications, with sophisticated designs usually constrained by limitations of volume, mass and power. In particular, for 2-phase gas/liquid separation in microgravity, centripetal acceleration or capillary action is used to remove liquids without the aid of gravity-driven buoyancy. These systems have often been prone to failure due to fluid fouling caused by biological reactions or mineral scaling, which can clog mechanical systems and degrade the performance of capillary-based systems. In turn, these failures can cause increased maintenance cost and overall crew labor burden.

Long duration space missions, such as expected for a Lunar Outpost or a Mars transit, will drive the need for hardware that is less prone to fouling failure and generally more robust and sustainable. One application that would benefit from innovation is wastewater management, wherein wastewater fouling can be accommodated by the design of the fluid management hardware as opposed to its occurrence being detrimental to the desired process.

This paper presents challenges associated with spacecraft water system fouling and suggests alternative approaches that move toward increased sustainability. Design considerations are presented wherein systems may be capable of accommodating, or potentially even benefiting from, fluid/surface fouling. Suggestions for a shift in the method of testing and evaluating spacecraft management system prototypes are offered to better bound expected operational conditions, providing more realistic performance data. Two examples of sustainable spacecraft fluid management systems that incorporate these design considerations are presented herein as case studies. One system is conceived for short duration microgravity flight, and the other for long duration planetary use. They are unified by accommodating fluid fouling, rather than preventing it, to achieve more sustainable and robust performance.

Spacecraft Fluid Management

In a microgravity environment, separation of immiscible fluids (i.e. gas and liquid) does not occur naturally, as it does on Earth due to buoyancy. In such situations, surface tension and wetting forces become the dominant influence on the liquid behavior. The Space Shuttle and the International Space Station (ISS) both use rotary fans for water separation from an airstream, which are known to be susceptible to failure due to fouling, since the tight tolerances and small orifices do not readily accommodate the resultant blockage that can occur from biological or inorganic mass buildup. This potential for clogging adds another concern in addition to the already generally increased likelihood of failure due to moving parts needed for rotating equipment (Johnson 2002; Puttkamer 2008).

Capillary action is regularly used for the control of liquids in various spacecraft systems, such as propellant and cryogen management or in thermal fluid loops for temperature control (Weislogel, Thomas et al. 2009). Large length-scale capillary systems such as these tend to exploit container geometry and fluid properties to passively transport fluids to desired positions for a variety of purposes. Unfortunately, such methods have only been confidently established for well characterized systems with favorable wetting conditions.

In contrast to state-of-the-art mechanical approaches, it is anticipated that passive capillary driven liquid phase separation is feasible in place of active rotary separators for wastewater applications, where the wetting and fouling characteristics can vary widely. In a recent study, a passive capillary-driven 'static phase separator' was developed and tested in a reduced-gravity environment to demonstrate successful air/liquid separation under highly variable wetting conditions (Weislogel, Thomas et al. 2008). When the system was operated within design specifications, it achieved 100% separation in nearly 100% of the tests performed, and with fluids of widely varying contact angles.

In general, geometry-based design considerations based on this principle can be used to improve the operational reliability of capillary-based microgravity fluid management systems. A design strategy begins to emerge when complemented by the following additional considerations.

Fluid Treatments

In a related study, Thomas and Muirhead (2009) observed that certain aspects of wastewater fouling can improve wetting characteristics. They found that although vacuum drying and large defects tended to increase θ_{adv} , crystal growth and biofilm growth actually lowered θ_{adv} . They also noted that the use of pretreatments generally increased θ_{adv} . These trends indicate that promotion of wastewater fouling may be exploited to significantly decrease θ_{adv} and thereby improve performance of capillary-based fluid management systems.

The use of oxidizing pretreatment chemicals for spacecraft wastewater is intended to prevent urea hydrolysis and the subsequent biofilm and precipitate formation that tends to foul and clog hardware such as rotary fan separators, vacuum orifice, or water recovery systems. In contrast, the absence of pretreatment chemicals likely results in an increased prevalence of biofilm formation and small crystalline growth, which has been shown to significantly lower the contact angle by up to 44° with 95% confidence (Thomas and Muirhead 2009). This response can be utilized by design to increase the performance of a capillary-based wastewater management system. Consequently, an alternate design strategy coinciding with the use of a capillary-based system might be to eliminate the need for pretreatment chemicals intended to prevent fouling, and deliberately allow wastewater fouling to occur in the liquid management system.

Lunar Outpost Water Recovery

As missions become extended in duration and move toward more self-reliant operations, new demands are placed on the life support system design. Thus far, all indications have suggested that the lunar outpost water recovery systems will be evolved from current spacecraft technologies, including urine pretreatment, distillation, and brine dewatering (NASA 2005). However, these technologies were developed for microgravity compatibility, and may carry undesirable fouling and failure mode heritage from this environment.

Unlike orbiting spacecraft, a lunar outpost will exist in a fractional Earth gravity environment ($\sim 0.166g_0$) with abundant natural resources including lunar regolith, vast open surfaces, and plentiful sunlight. Gravity can at the very least make complex microgravity compatible technologies unnecessary, and at best be advantageously utilized in a wastewater recovery process. Meanwhile, the outpost may not have ready access to Earth resupply, making consumables and maintenance of greater concern when conducting design trade studies. Lunar surface conditions are perhaps more analogous to the terrestrial environment than to microgravity space flight. For these reasons, the appropriate technology development approach for lunar outpost hardware may likely be adapting terrestrial technologies for use in a hypogravity environment, rather than modifying microgravity space flight technologies.

As part of a wastewater management system for a planetary base, an alternative filtering method is suggested. The aforementioned fouling studies indicated that wastewater can be expected to form biofilms, amorphous crystalline deposits, and large crystals on solid surfaces. These constituents are similar to those found in terrestrial water treatment systems, and can easily be filtered out. For example, wastewater in a lunar outpost could be encouraged to foul, and then these fouling constituents could then be removed by filtering. Potentially, lunar

regolith could be used as a media filter. Filtered wastewater is then delivered to the primary downstream processors. By precipitating crystalline constituents, it is feasible to expect a higher recovery rate and lower energy cost for the primary processors, which are limited by the solubility of the ionic concentrations.

A primary NASA Exploration Life Support technology activity is “reducing life support consumables and improving system performance and robustness,” (Barta and Ewert 2009). This sustainable water recovery concept addresses this gap through the innovative use of partial gravity, solar energy and lunar regolith in place of pretreatment chemicals and primary processors (Thomas, Leidich et al. 2009).

High Fidelity Environmental Technology Testing

In addition to the technical design considerations, it is possible that more sustainable spacecraft fluid management technologies might also be developed by reconsidering the methods in which they are typically tested under highly controlled conditions. The goal is generally to conduct defined tests that produce predictable and reproducible results akin to how basic scientific research is carried out. Once these systems are in space, however, they often fail in complex, unforeseen ways leaving the engineers frustrated and the systems in disuse.

Designing, testing and evaluating spacecraft fluid management systems is an engineering challenge more than it is a basic science research challenge. Rather than examining fundamental processes, engineers are generally more interested in how well a given system meets operational requirements. Testing protocols, therefore, should be adjusted to reflect this goal. Systems should not need to be fully characterized under precise and controlled environments; rather results from complex and compounded conditions within defined boundaries should be compared to stated performance requirements.

While this approach may seem like standard engineering practice, it is in fact a departure from the methods in which most spacecraft fluid management systems are tested, perhaps a consequence of the rarity and expense of ‘in-space’ field testing. Specifically, the typical approach today is to control the testing environment in such a way that any particular requirement is evaluated in relative isolation. For example, ground tests with fluid systems often use ersatz with over-simplified conditions that do not fully represent the actual environment that produces the appropriate complex surface conditions in which the fouling occurs. Engineering performance tests consequently should be less concerned with fully characterizing a single parameter in favor of gaining confidence in the system’s overall robustness and sustainability across a range of expected conditions. In this manner, the resultant designs will necessarily be capable of accommodating, if not exploiting, fluid fouling, making the next generation of spacecraft life support and fluid handling systems more robust and sustainable.

Conclusion

Rather than attempting to prevent or reduce fouling, which can result in wastewater system failures, sustainable fluid management concepts can be designed to accommodate, perhaps

even benefit from, biofouling and mineral scaling. Design considerations including geometry guidelines for capillary-based fluid separators capable of handling highly variable wetting conditions, discontinued need for pretreatment chemicals, and wastewater fouling filtration offer feasible approaches.

Additionally, rather than evaluating technologies within narrowly controlled experimental conditions that might not accurately reflect actual complex operational environments, water handling systems can be operationally verified over a reasonable envelope of expected conditions to better ensure their reliability. These considerations can be applied to myriad terrestrial and spacecraft sustainable fluid management technologies.

Collectively, the design considerations and application examples presented here are unified by the approach of accommodating fluid fouling to achieve more sustainable and robust systems.

References

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